APPENDIX B. DEVELOPING LOCAL HAZARD CONDITIONS BASED ON REGIONAL OR LOCAL SEA-LEVEL RISE USING THE NRC 2012 REPORT[36]

Determining local hazard conditions is one of the first steps in sea-level rise planning efforts. Because sea-level rise varies locally, this analysis must be performed on a site-by-site basis, and obtaining data or conducting research at the correct geographical scale is something project applicants and planners should prioritize. The 2012 NRC Report is the best available science on California's regional sea-level rise, and it should be used when sea-level rise projections are needed.

Much of the research by the IPCC and others, and even the material in the 2012 NRC Report, has focused on global and regional changes to mean sea level. However, the coast is formed and changed by local water and land conditions. Tide range influences where beaches, wetlands and estuaries will establish; waves and currents are majors drivers of shoreline change; storms and storm waves are often the major factors causing damage to coastal development. It is local conditions that influence beach accretion and erosion, storm damage, bluff retreat and wetland function.

Local water levels along the coast are affected by local land uplift or subsidence, tides, waves, storm waves, atmospheric forcing, surge, basin-wide oscillations, and tsunamis. Some of these factors, such as tides and waves, are ever-present and result in ever-changing shifts in the local water level. Others, such as storms, tsunamis, or co-seismic uplift or subsidence, are episodic but can have an important influence on water level when they occur. The following section discusses these factors in the context of sea-level rise and how they are incorporated into planning and project analysis.

In most hazard situations, high water will be the main project or planning concern. For wetlands, low and high tides will be of concern and, in some special situations, such as for intake structures, low water might be the main concern. In some situations where low water is the concern, current low water is likely to be the low water planning condition and there may be no need to factor future sea-level rise into those project or planning situations. The following Text Box identifies some of the key situations or indicators that may be important for coastal managers and applicants to consider sea-level rise during project review.

[36] This guidance provides specific direction for using the materials from the 2012 NRC Report. As the best available science for sea-level rise changes, Commission staff will assess whether revisions to this guidance will be needed. Until this is revised, readers should use their best judgment in applying this guidance for other reports. For example, information is provided for developing sea-level rise projections for years other than 2030, 2050, or 2100. If the next report provides projections for different years than 2030, 2050, or 2100, the new projection years can be substituted for the NRC years. If new projections are found to improve the information from the NRC report, the formula for interpolation of the NRC projections should not be used.

General Situations when Sea-Level Rise Analysis Should be Considered

Project or planning site is:

- Currently in or adjacent to an identified floodplain
- Currently or has been exposed to flooding from waves
- Currently in a location protected from flooding by constructed dikes, levees, bulkheads, etc.
- On or close to a beach, estuary, lagoon, or wetland
- On a coastal bluff with historic evidence of erosion
- Reliant upon shallow wells for water supply

For situations where future sea level conditions will be important, the following steps are provided as guidance for determining local hazards. Figure 9 shows the general progression for going from global sea level projections to the possible consequences or impacts that can result from local water levels.

1. **Determine appropriate planning horizon or expected project life.** Determine the appropriate planning horizon or expected project life (which is often provided in the LCP). For many planning efforts, more than one planning horizon may be needed.

2. **Determine regional sea level projections for planning horizon or expected project life.** Select an appropriate regional sea-level rise projection based on the planning horizon or expected project life. For scenario-based planning and project analysis, more than one sea-level rise projection should be used.

3. **Modify regional sea-level rise projections for local vertical land motion:** Modify the regional sea-level rise projection to account for local vertical land motion, if appropriate. In locations with a large discrepancy between the recorded sea level trend and the regional projections (such as Humboldt Bay), modifications of the regional sea-level rise projections will be necessary. In most situations, the values from the NRC Report can be used without modification.

4. **Project tidal elevations and future inundation:** Project future tidal elevations (mean higher high, mean lower low, etc.), based on historic tidal records and the appropriate NRC (2012) sea-level rise projection.

5. **Determine water level changes from surge, El Niños, PDOs, etc.:** Determine projected water level changes from storm surge, atmospheric pressure, the El Niño/Southern Oscillation, the Pacific Decadal Oscillation or other basin-wide phenomena.

6. **Estimate beach, bluff, and dune change from erosion:** Estimate likely future beach erosion and beach scour, or bluff erosion, if bluffs are present, for appropriate planning horizon or expected project life, including if possible, the changes in erosion due to sea-level rise.

7. **Determine potential flooding, wave impacts, and wave runup:** Determine projected wave impacts and wave runup from a 100-year storm event, for planning horizons or expected project life, based on high tide and other water level changes, future beach and bluff erosion and future beach scour.

8. **Examine potential flooding from extreme events:** Examine possible impacts from extreme events, such as storms with return intervals greater than 100 years, tsunamis, etc.

9. **Repeat as necessary:** Repeat for each planning horizon or sea-level rise scenario.

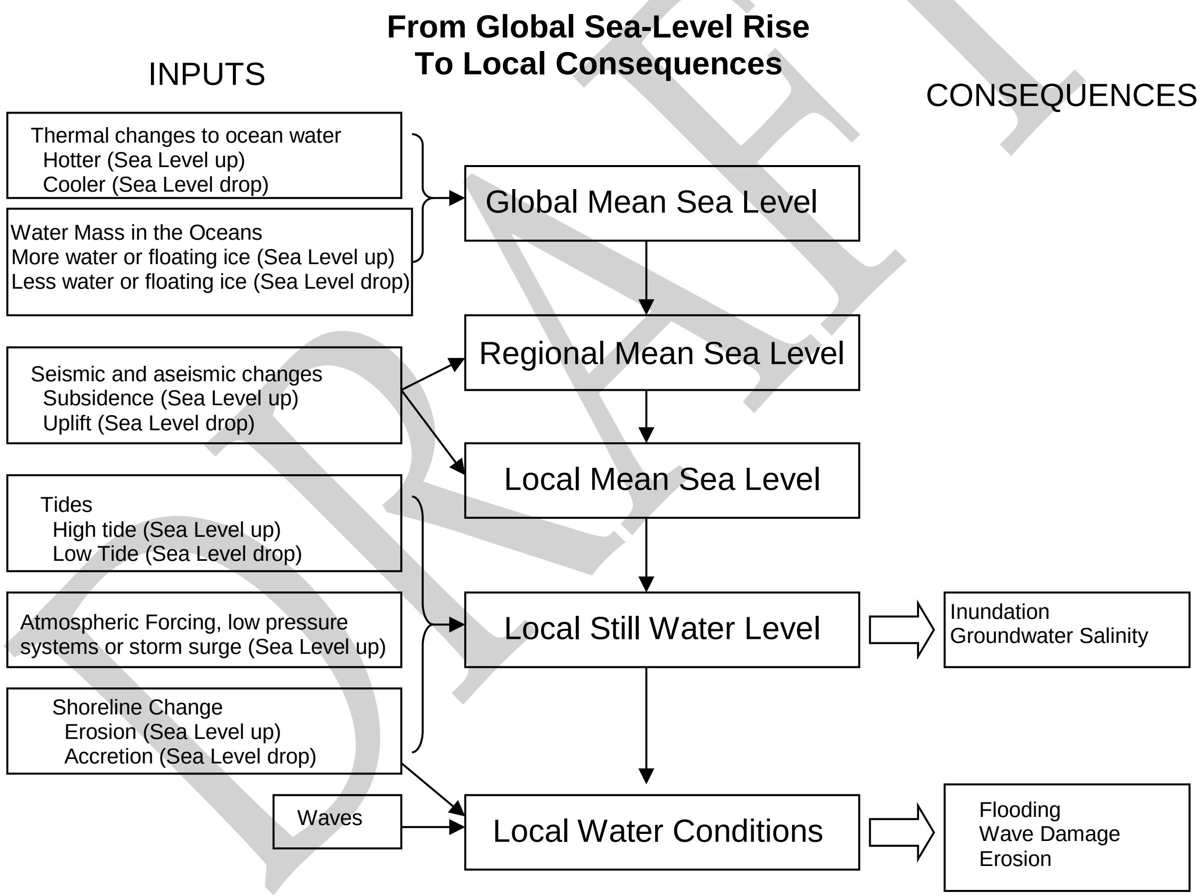


Figure 9. General process for changing global sea-level rise for local conditions.

Step 1 – Determine Appropriate Planning Horizon or Expected Project Life

The first step in a sea-level rise analysis is to determine the appropriate planning horizon or expected life of the project. The longer the life of a project or planning horizon, the greater the amount of sea-level rise the project or planning area will experience. Also, since future sea level is not expected to be linear, the amount of sea-level rise that can be expected to occur over some length of time will increase with a later starting time. For example, a project built today will experience less sea-level rise over a 50-year lifetime (about 24 inches or 61 centimeters using the higher projections for south of Cape Mendocino) than the same project if it were built in the year 2050 (about 40 inches or 101 centimeters, using the higher projections for south of Cape Mendocino). Thus, it is important to understand the projected life of a structure and the planning horizon before starting an analysis for sea-level rise concerns.

Local governments should select their planning horizons to evaluate a broad range of planning concerns. Planning horizons might address the 20-year time period for general plan updates to the long-range planning necessary for infrastructure and new development. At the project level, the LCP can often provide insight into the time period that should be considered for the expected project life. At present, most LCPs provide only a single standard for the expected life of structure or development, normally 50, 75, or 100 years. Future LCPs and LCPAs may find it useful to provide greater guidance on expected project life, with differentiations among major development or use classifications.

Outcome from Step 1: *Step 1 provides an identification of the years and time periods that will be used in analysis of the project or development of a plan*.

Step 2 – Determine Regional Sea Level Projections for Planning Horizon or Expected Project Life

The second step in an analysis of sea-level rise is to determine the regional sea-level rise projections that are appropriate for the proposed project or planning effort. At present, the 2012 NRC report provides the best available science for regional sea-level rise projections. However, these projections are provided as changes in sea level from the year 2000 to 2030, 2050, and 2100. If the planning horizon or expected project life is at or very close to these years, the projections can be used as given. In many cases, these projections will need to be modified to obtain projections for the time periods of interest. There are several modifications that may be appropriate:

- Developing sea-level rise projections for years other than 2030, 2050 or 2100.
- Developing sea-level rise projections for planning or projects with start times other than the year 2000.
- Developing sea-level rise projections for planning or projects with an anticipated life beyond the year 2100.

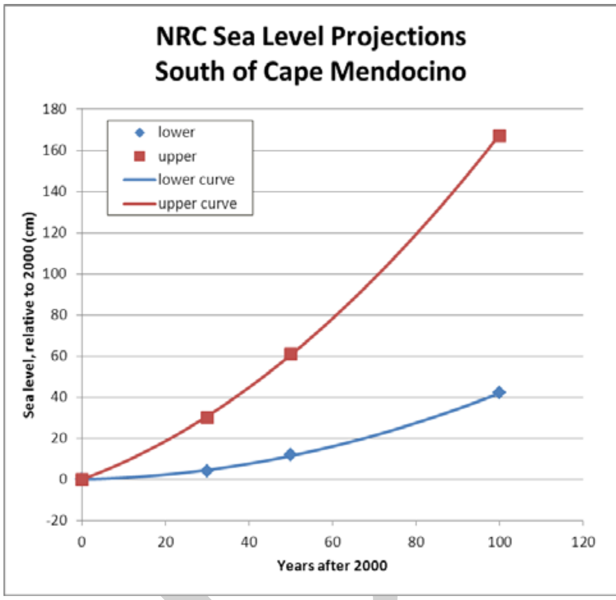
Guidance for all three situations is provided below.

Projection of sea-level rise for years other than 2030, 2050, and 2100

For sea-level rise projections for years within a few years of those used in the NRC projections, the 2030, 2050, and 2100 projections can be used. However, for years that are not close to these years, sea-level rise projections should be interpolated from the projections. Two methods are recommended for establishing a projection value for a specific year: (1) conduct a linear interpolation[37], or (2) use the "best fit" equations that are provided below. At this time, both are acceptable.

1. Linear Interpolation: One method for establishing a sea-level rise projection for a specific year is linear interpolation between the two known or given projections. The most immediate time periods before and after the desired time period should be used. For example, for a proposed project south of Cape Mendocino with an expected life till 2075, the upper range for the sea-level rise projections closest to this time period are 2.0 feet (61cm) for 2050 and 5.48 feet (167 cm) for 2100.

SLR(2075) = SLR(2050) + ((SLR2100 – SLR2050) x (2075 - 2050/(2100 – 2050))
= 2.0' + ((5.48' – 2.0')(2075 – 2050)/(2100 – 2050)
= 2.0' + ((3.48)(25)/50) = 3.74' (114 cm)



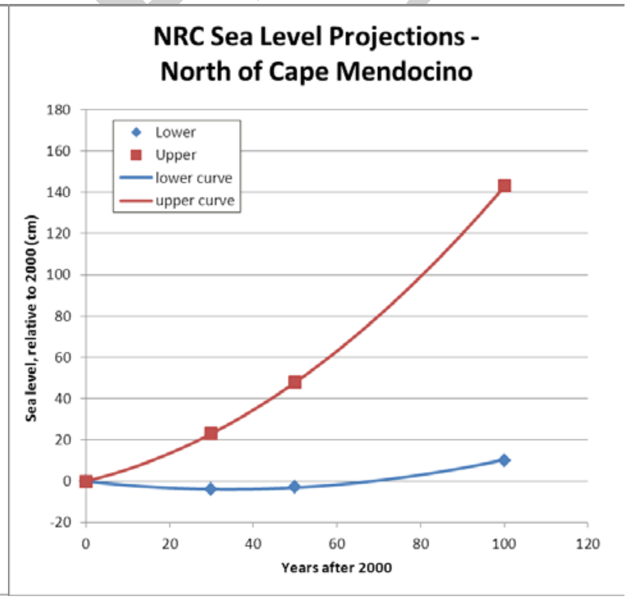


Figure 10. Sea-level Rise Projections, North and South of Cape Mendocino (from NRC Report)

2. <u>Use Equation:</u> A second option is to use one of the following quadratic equations that represent the "best fit" for each of the above sea-level rise curves. These equations can be used to project sea-level rise for years other than 2030, 2050, and 2100. These equations provide sea-level rise in centimeters. If English units are desired, the projections will need to be converted using 1 cm = 0.0328 feet, or 1 cm = 0.394 inches.

[37] Linear interpolation is a method for filling in gaps in data or information that assumes that two known data points that bound the unknown point can be connected with a straight line. The missing information is estimated through reference to this line. The example in the text provides an example of the mathematical steps for linear interpolation.

Equations for Sea-Level Rise Projections, based on values from the NRC Report (NRC 2012)

North of Cape Mendocino

- Upper Range -- Sea Level Change (cm) = $0.0094t^2 + 0.4868t$ (Equation B-1)
- Lower Range – Sea Level Change (cm) = $0.0033t^2 - 0.2257t$ (Equation B-2)

South of Cape Mendocino

- Upper Range – Sea Level Change (cm) = $0.0093t^2 + 0.7457t$ (Equation B-3)
- Lower Range Sea Level Change (cm) = $0.0038t^2 + 0.039t$ (Equation B-4)

Where "t" is the number of years after 2000

For example, if the proposed project were south of Cape Mendocino, with an expected life of 75 years, use Equation B-3, with t = 75.

$$Sea\ Level\ Change\ (cm) = 0.0093 \times (75)^2 + (0.7457 \times 75) = 52 + 56 = 108\ cm$$

The sea level change projected using the equation is slightly less than that projected by linear interpolation because the NRC's sea level curves, shown in Figure 10, are concave upward (sea-level rise is expected to accelerate over the 21st century). A line between any two points on the curve will always be slightly higher than the curve itself.

As noted previously, either method is acceptable for estimating sea-level rise for a year that has not been provided in the NRC Report.

Ranges of sea-level rise projections that do not start at the year 2000

The NRC sea-level rise projections use the year 2000 as the base year. Since there has been little, if any, measureable rise in sea level since 2000 for most locations in California (Bromirski et al., 2011; NOAA Tides and Currents, 2013), there is little reason or justification for adjusting sea-level rise projections from 2000 to a more current start date. All of the latent sea-level rise might occur quickly, providing sea level conditions consistent with the future projections. Thus, when the needed sea level value is a projection of the future sea level that will be experienced by a proposed project for a proposed planning situation, there is no need to adjust the 2012 NRC projections for a different project starting year.

If the needed sea-level rise value is the range of sea level that might be experienced over a future time period, as might be used for planning a wetland restoration project, then adjustments to the starting point for sea-level rise projections may be necessary. Given the recent lack of sea level change in California, it is suggested that such planning or design efforts not do any adjustments to the sea-level rise projections for start dates prior to about 2015 or 2020. When the range of sea level exposure is needed for a future planning scenario, this sea level range can be developed by interpolating the sea level projections for the starting and ending years, and obtaining the difference in sea level by subtracting these two. For example, if a restoration project will be designed to take into account the sea-level rise that will occur from 2040 to 2060, use Equations

B-1, B-2, B-3 or B-4 to get SLR(t1) and SLR(t2) and subtract SLR(T- 40 years) from SLR(t= 60 years) to get the range of sea-level rise from 2040 to 2060.

Sea-level rise projections beyond 2100

Sea-level rise is expected to continue well past the year 2100, despite the termination of most projections at that year.[38] The uncertainty associated with any projections for sea level grows significantly as the time period increases. There are large uncertainties in projections for sea-level rise in the 2100 time period. However, long-term planning and projects requiring long lead times or large capital expenditures need to consider conditions that might occur in the next 100 or more years.

At this time, there are no studies that specifically address projections of sea-level rise for California beyond the year 2100. The NRC projections stop at 2100 and provide no guidance for extrapolation of the range of sea-level rise projections past that time. The equations provided above, while most appropriate for interpolation up to 2100, can be used to extrapolate sea-level rise for a few years beyond 2100. For projections beyond about 2105 or 2110, alternative methods should be considered for developing sea-level rise projections.

1. Use the NRC projections for 2050 and 2100 to develop a linear trend beyond 2100.
2. Use sea-level rise rates that have been developed in recent years, some of which are provided in Table 7.
3. Interpolate between the NRC projections, and one of the reports that provides projections of global sea-level rise for 2200 or 2300 (some of which are listed in Table 8).

None of these options will provide sea-level rise projections that have a confidence similar to the NRC projections. Eventually, there may be regionally appropriate projections for sea level into the 22nd and 23rd centuries. Until then, some assumptions may need to be used for analysis that goes into these time periods. It is clear that sea level will continue to rise past 2100, and any effort to look beyond the year 2100 will be better than using projections of sea-level rise for 2100 as the upper limit of what might happen beyond that time. Nonetheless, it is critical that long-range planning efforts and projects with long design lives include provisions to revisit SLR hazards periodically, and to make adjustments as new science becomes available.

[38] For example, a recent study by Levermann et al. (2013) suggests that, due to slow-acting ice sheet processes and climate feedbacks, global warming of just 2 ºC (at the low end of current projections for the 21st century) would "commit" the planet to between 2.6 – 7.5 meters of sea-level rise over the next 2,000 years.

Table 7. Range of Global Sea-level Rise (from Nichols et al., 2011)

Sea-level rise Feet/century (Meters/century)	**Methodological Approach**	**Source**
1.6 – 4.6 (0.5 – 1.4)	Semi-empirical projection[b]	Rahmstorf 2007
2.6 - 7.9 (0.8 – 2.4)[a]	Paleo-climate analogue	Rohling et al.2008
1.8 – 3.6 (0.55 – 1.10)	Synthesis[b]	Vellinga et al. 2008
2.6 – 6.6 (0.8 – 2.0)	Physical constraints analysis[b]	Pfeffer et al. 2008
1.8 – 3.0 (0.56 – 0.92)[a]	Paleo-climate analogue	Kopp et al. 2009
2.5 – 6.2 (0.75 – 1.90)	Semi-empirical projection[b]	Vermeer & Rahmstorf 2009
2.4 – 5.2 (0.72 – 1.60)[c]	Semi-empirical projection[b]	Grinsted et al. 2009

[a] Higher rates are possible for shorter periods
[b] For the 21st century
[c] For the best paleo-temperature record.

Table 8. Projections of Global Sea-level rise Beyond 2100

Projection Scenario[a]	Sea-level rise for 2300, referenced to 2000 (Schaeffer et al., 2012) ft (m)	2300 Sea-level rise rate (Schaeffer et al., 2012) inches/yr (mm/yr)	Sea-level rise for 2500, referenced to 2000 (Jevrejeva et al., 2012) ft (m)
RCP4.5	7.0 – 17.3 (2.12 – 5.27)	0.24 – 0.74 (6 - 20)	2.4 – 14.1 (0.72 – 4.3)
RCP3PD	3.9 – 10 1 (1.18 – 3.09)	0.04 – 0.35 (1 - 9)	0.4 – 5.7 (0.13 – 1.74)
RCP6			3.4 – 19.0 (1.03 – 5.79)
RCP8.5			7.4 – 37.8(2.26 – 11.51)
Stab 2°C	5.1 – 13.2 (1.56 – 4.01)	0.16 – 0.55 (4 – 14)	
Merge400	2.8 – 7.7 (0.86 – 2.36)	-0.08 – 0.12 (-2 – 3)	
Zero 2016	2.5 – 6.8 (0.76 – 2.08)	0.04 – 0.24 (1 – 6)	

[a] See referenced reports for details on projection scenarios.

Outcome from Step 2: *Step 2 provides a regional sea-level rise projection that can be used to for project analysis or development of a plan.*

<u>Step 3 – Modifying Regional Sea-Level Rise Projections for Local Vertical Land Motion</u>

NOTE: This step is necessary only for project analysis or planning efforts in the vicinity of Humboldt Bay and the Eel River estuary. For all other areas, this step can be skipped.

Changes in land level, either from uplift or subsidence, will affect the sea level measured at that location. Relative sea level, also known as local sea level, is the term used to describe changes to locally measured sea level from land uplift or subsidence (i.e. sea-level rise relative to land change). For land that is subsiding while sea level is rising, the rates are additive such that regional sea-level rise will be the sum of global sea-level rise plus land subsidence. If the land is undergoing uplift, the uplift will cancel out some or all sea-level rise, and regional sea level will be global sea-level rise minus land uplift.

Relative Sea Level Change Rate = Sea-level rise Rate + Land Subsidence Rate

Or

Relative Sea Level Change Rate = Sea-level rise Rate – Land Uplift Rate

The NRC Report has adjusted regional sea level projections for the large-scale uplift and subsidence that has been observed along the coast. However, the NRC projections have not taken into account the local variations in vertical land motion that occur. However, in guidance developed for the OPC, a three-member subcommittee of the OPC Science Advisory Team (OPC-SAT) advised using the NRC projections, without modification, for all California locations except between Humboldt Bay and Crescent City. The OPC-SAT subcommittee stated, “We do not believe that there is enough certainty in the sea-level rise projections nor is there a strong scientific rationale for specifying specific sea-level rise values at individual locations along California’s coastline.” (OPC, 2013, pg. 10)

Site-specific modifications to the NRC projections will be needed for the Humboldt Bay and Eel River estuary area, where the tide gauge records show a very different sea-level rise trend than what is projected for the North of Cape Mendocino region. The OPC-SAT Subcommittee advises that for the northern California coast, sea-level rise projections be developed from the recorded tide gauge rates at Humboldt and Crescent City “augmented by any future acceleration in rates of sea-level rise … for the areas closest to these gages, with intermediate values for the areas between them” (OPC 2013 pg. 11). Table 9 shows the historic sea level trend, based on tide gauge records for the North Spit of Humboldt Bay and for Crescent City that can be used for local sea-level rise adjustments for the area north of Cape Mendocino.

Table 9. Sea Level Trends for Humboldt Bay, CA and Crescent City, CA

Location	Period of Record	Sea Level Trend (ft/century)	Sea Level Trend (mm/yr)
Humboldt Bay	1977 - 2013	1.36 +/- 0.38	+4.14 +/- 1.15
Crescent City	1933 - 2013	-0.27 +/- 0.11	-0.81 +/- 0.33

Source: NOAA Tides and Currents, 2013, “Updated Mean Sea Level Trends”. Retrieved July 2, 2013 from http://tidesandcurrents.noaa.gov/sltrends/sltrends_states.shtml?region=ca.

The OPC-SAT Subcommittee recommended using the NRC sea-level rise projections for most locations south of Cape Mendocino, without local adjustments for vertical land motion. This recommendation should be given serious consideration. If a local government or project applicant should decide to include local vertical land motion, for a particular reason, the local land changes should replace the regional projections of vertical land change assumed by the NRC report (from Table 5.3 of the NRC Report and reproduced in Table 10). If local trends are applied to the regional projections, the inclusion of local uplift or subsidence will compound the regional land changes already included in the NRC Report.

Table 10. Regional Vertical Land Motions used in NRC Regional Sea Level Projections

	North of Cape Mendocino				South of Cape Mendocino			
	Centimeters		Inches		Centimeters		Inches	
	Ave.	Range	Ave.	Range	Ave.	Range	Ave.	Range
2000 – 2030	-3.0	-7.5 - +1.5	-1.1	-3.0 - + 0.6	4.5	0.6 – 8.4	1.8	0.2 – 3.3
2000 – 2050	-5.0	-12.5 - + 2.5	-2.0	-4.9 - +1.0	7.5	1.0 – 14.0	3.0	0.4 – 5.5
2000 – 2100	-10.0	25.0 - + 5.0	-4.0	-9.8 - +2.0	15.0	2.0 – 28.0	5.9	0.8 – 11.0

NOTE: Negative values show uplift and positive values show subsidence. If no sign is used, values are positive for subsidence.)

The NRC report provides some vertical land motion information to assist with modifying regional sea-level rise for local conditions. Appendix A of the NRC Report provides vertical land motions for eight California locations (Crescent City, San Francisco, Alameda, Port San Luis, Santa Monica, Los Angeles, La Jolla and San Diego). In addition, Appendix D of the NRC Report, “Long-term Tide Gage Stability from Land Leveling” provides a discussion on tide gauge observations, with long-term vertical land motion for Crescent City, San Francisco, Port San Luis, Los Angeles, and San Diego.

Local vertical land motion can be influenced by many of the factors. Each factor may alter vertical land motion differently and detailed projections of future vertical land motion may need to be developed from the trends for each of the individual components. Seismic activity can often influence vertical land motion and vertical land motion trends during times of high seismic activity may be very different from those recorded during periods of low seismic activity. Groundwater pumping and fluid extraction can have a major influence on vertical land motions. But, effects from fluid extraction will be localized and vertical land motion measurements close to the extraction areas will be needed to quantify local vertical land motion. Historic trends in vertical land motion for one location may not be appropriate for another location, even one that is only 5 or 10 miles away. Several programs have been established to better understand vertical land motion, but they have been in operation for at most a few decades, and long-term projections of vertical land motion are difficult to develop. Projections of local land motion introduce another layer of uncertainty into sea-level rise projections. When local vertical land motions are used to modify the regional sea-level rise projections, there should be at least one scenario that examines the consequences from the unmodified regional sea-level rise range.

Outcome of Step 3: *Step 3 provides a locally modified sea-level rise projection that can be used for project analysis or development of a plan.*

Step 4 – Project Tidal Range and Future Inundation

One of the most basic examinations of changing sea level conditions has been to determine the new intersection of mean sea level or other tidal levels with the shoreline. This has been called the "bathtub" analysis since it looks only at the expansion of areas that will be inundated (i.e. regularly submerged under water). The inundation level will move up in elevation and the zone of inundation will move inland, generally following the existing slope of the beach or shore. So the future inundation level can be approximated as the sum of the current water level plus future regional mean sea-level rise. The future inundation zone will be where this water level meets land.

Future Water Elevation = Current Water Elevation + Projected Sea-level rise

Future Water Location = Intersection of Elevation with Future Shore Location

For example, future sub-tidal levels would be the current subtidal limit plus projected regional mean sea-level rise. Future intertidal zones would be bounded by the current higher high tide level plus projected regional mean sea-level rise and lower low tide levels plus projected regional mean sea-level rise.[39] For some projects, such as wetland restoration, the identification of future inundation zones may be the only sea level analysis needed for project evaluation. If the shoreline is eroding, the location of this elevation would need to also incorporate the rate of erosion. So, not only will the intertidal zone move up in elevation, if the shoreline is expected to erode due to increased wave attack, the intertidal zone will be both higher than and inland of the current zone.

Inundation will extend to the location of the new inundation elevation. On beaches with a gradual slope, this can move the inundation location significantly inland, based on the slope (geometric conditions) of the beach. (This type analysis is often called the Bruun Rule). On a stable beach with a slope of 1:X (Vertical:Horizontal), every foot of vertical sea-level rise will move the inundation area horizontally X feet inland. For a typical 1:60 beach, every foot of sea level would move the inundation zone inland by 60 feet. If the beach is eroding, the loss due to inundation will add to the loss from erosion.

Figure 11 shows the influence of tides and sea-level rise on low-wave energy beaches. Table 11 provides some useful resources for inundation studies. For the open ocean coast, where waves are a dominant feature of a beach, the changes to the beach need to include waves, as discussed later in this section.

[39] Historic trends of high and low tide have changed differently than mean sea level (Flick et al. 2009). Based on historic trends, the changes to various tidal elements are likely to track closely with, but not identically with, changes to mean sea level. The future variability of changes to the tidal components, compared with changes to mean sea level will normally be within the uncertainty for sea-level rise projections and can be ignored for almost all situations. As this phenomenon of tidal change is better understood and can be modeled, it may be appropriate in the future to include the changes in tidal components into the analysis of inundation and various water level projections.

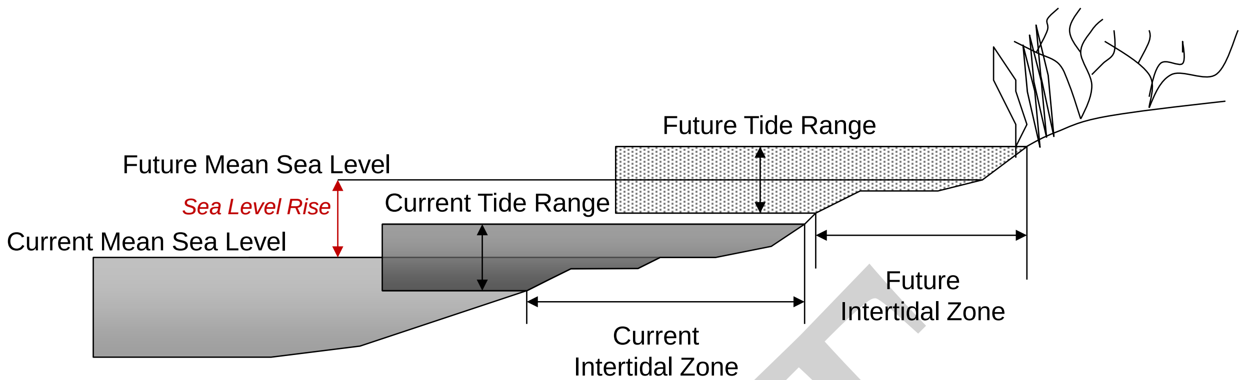


Figure 11. Sea-level rise and Changes to Tide Range and Intertidal Zone.

Table 11. General Resources for Inundation Studies

Resource	Specifics of Information	Source
Aerial Photographs	Useful for general information on shoreline trends Ortho-rectified photos can help quantify trends	California Coastal Records Project; www.californiacoastline.org Huntington Library Local Libraries
LIDAR	Fairly detailed topography Can provide GIS layers for current conditions Comparable with LIDAR data sets for temporal changes	NOAA Coastal Services Center - http://www.csc.noaa.gov/data/index.html
Topographic Maps	Often not at a scale to distinguish small changes in water levels	USGS Map Center - http://www.usgs.gov/pubprod/maps.html
NOAA Sea Level Rise Viewer	Useful to show changes in water level location if there are no changes in the land due to erosion.	NOAA's Digital Coast http://www.csc.noaa.gov/digitalcoast/tools/slrviewer
Tidal Data	Measured and predicted tidal components for locations along the open coast and in bays.	http://tidesandcurrents.noaa.gov/
Cal-Adapt – Exploring California's Climate	Shows coastal areas that may be threatened by flooding from a 1.4 meter rise in sea level and a 100-year flood event. Maps do not now include any influence of beach or dune erosion or existing protective structures.	http://cal-adapt.org/sealevel/

Outcome from Step 4: *Step 4 provides information on the projected changes to the tidal range and future zones of inundation. For locations without any influence from erosion, storm surge, or wave energy, the identification of new inundation areas may be sufficient for project analysis and planning efforts. This projected new inundation area may also be useful for anticipating the likely migration of wetlands and low-energy water areas or as input for analysis of changes groundwater salinity. For most open coast situations, this information will be used to inform further project analysis and planning that examines erosion, surge and storm conditions.*

Step 5 – Determine Water Level Changes from Surge, El Niños, PDO, etc.

Estimates of surge, El Niño and PDO water elevation changes are developed primarily from historic records. There are no state-wide resources for this information, although it may be included in one of the regional Coastal California Storm and Tide, Wave Studies prepared by the US Army Corps of Engineers. General guidance on water level changes that can be expected from surge and El Niños is provided in Table 12.

The remaining discussion provides general information on some of these phenomena. It is provided to acquaint readers to the main issues associated with each. Readers with a strong background in ocean-atmospheric conditions may want to skim or skip the rest of this section.

The Pacific Ocean is a complex system. Sea level in the Pacific Ocean is a response to multiple oceanic and atmospheric forcing phenomena, occurring with different intensities and at different temporal and spatial scales. Some phenomena may reinforce each other, while other may act in opposition, essentially canceling each other out. Scientists and researchers are attempting to identify the various signals from the multiple phenomena, but these are nascent sciences and there is still much we need to learn.

Regional water levels can be modified by surge as well as by high and low pressure systems. Surge is a short-term change in water elevation due to high wind, low atmospheric pressure, or both. It is most often associated with east coast and gulf coast hurricanes that can cause up to 15 or 20 feet (4 to 6 meters) or more of short-term water level rise over many miles of the coast. Along the west coast, storm surge is much smaller, and is rarely a coastal hazard, except in enclosed bays. In southern California it rarely exceeds one foot (0.3 meters) and in central California, it rarely exceeds 2 feet (0.6 meters). Surge becomes a concern because it is one of several cumulative factors that cause a temporary rise in sea level. Each rise may be small, but when they occur in combination or during high tides and with storms, they increase the threat of coastal flooding, wave impacts and erosion.

Two of the more recognized phenomena that affect water temperature in the Pacific are the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). ENSO cycles, which occur on inter-annual timescales (approximately 2-7 yr), involve ocean-basin-spanning changes in sea surface temperature (SST) and the depth of the mixed layer in the Equatorial Pacific, but also drive changes in ocean conditions and atmospheric circulation at higher latitudes. El Niño events result in the transfer of warm surface waters into the normally cool eastern equatorial Pacific, resulting in elevated SST and water levels along much of the west coast of the Americas. El Niños also tend to increase the strength and frequency of winter low pressure systems in the North Pacific. These events can persist for months or years at a time, and strongly influence local and regional sea level. For example, the pulse of warm water from the large 1982-83 El Niño caused water levels along the California to be elevated by approximately 0.4 - 0.7 feet (0.12 – 0.21 m) for many months, with short-term water elevation peaks up to about 1 foot (0.3 m) (Flick, 1998). The opposite phase of ENSO, characterized by unusually cool SSTs and lower water elevations along the eastern Pacific margin, are called La Niña events. Between El Niños and La Niñas are periods of neutral SST and water elevation changes.

The PDO is an ENSO-like pattern of SST and atmospheric variability occurring over multiple decades. In contrast to ENSO, the PDO is more strongly expressed in the North Pacific than in the tropics. The positive or warm phase of the PDO is associated with unusually warm surface water along eastern North Pacific (the western US coast), while the negative or cool phase PDO is associated with colder than normal water. As with the ENSO effects, the warm phase PDO has tended to cause elevated sea levels in the eastern Pacific and along the California coast, while the cool phase of the PDO tends to lower sea level in this region.

The PDO has basin-wide influence. Elevated water levels in one part of the Pacific are often accompanied by lowered water levels elsewhere. The cool phase PDO can result in a drop of water level along the eastern Pacific (western US coast) and a rise in water level along the western Pacific. Recently, sea level along the western Pacific has been rising about three times faster than the global mean sea-level rise rate (Bromirski et al., 2011; Merrifield, 2011). This does not mean the eastern Pacific will experience sea-level rise that is three times faster than the global mean sea-level rise when there is the next shift in the PDO, but does show that the PDO can have a major influence on basin-wide and regional sea level.

The above discussion of El Niño and the PDO suggests that there are well-understood, readily predicted changes in sea level that result from these phenomena. However, it is important to note that El Niños have varying strengths and intensities, resulting in different sea changes from one event to the next. And, changes in regional mean sea level along the eastern Pacific have not always shown a strong connection to the PDO cycles. An apparent jump in regional mean sea level occurred after the mid-1970s shift to the warm phase of the PDO, yet the expected continued rise in sea level along the West Coast seems to have been suppressed by other forces. Tide gauge records for the Washington, Oregon and California coasts have shown no significant interannual rise in sea level from 1983 to 2011 (Cayan et al., 2008; NOAA Tides and Currents, 2013; Bromirski et al., 2011). Bromirski et al. (2011 & 2012) postulate that persistent alongshore winds have caused an extended period of offshore upwelling that has both drawn coastal waters offshore and replaced warm surface waters with cooler deep ocean water. Both of these factors cause a drop in sea level that may have cancelled out the sea rise that otherwise would be expected from a warm phase PDO signal.

Water level changes from surge, atmospheric forcing, El Niños and the PDO can occur in combination. The water elevations changes from each factor may each be only about a foot or less (less than 0.3 meters), but they can cause changes in the water level over a time period of days, months, or a few years -- far more rapidly than sea-level rise. In combination, they can cause a significant localized increase in water level.

When high water conditions occur in combination with high tides, and with coastal storms, the threat of coastal flooding, wave impacts and erosion also increases. These conditions can be additive, as shown in Figure 12. Also, these changes in water level will continue to be important to the overall water level conditions along the California coast and they need to be examined in conjunction with possible changes due to regional sea-level rise.

As stated earlier, estimates of surge, El Niño and PDO water elevation changes are developed primarily from historic records. There are no state-wide resources for this information, although it may be included in one of the regional Coastal California Storm and Tide, Wave Studies prepared by the US Army Corps of Engineers. General guidance on water level changes that can be expected from surge and El Niños is also provided in Table 12.

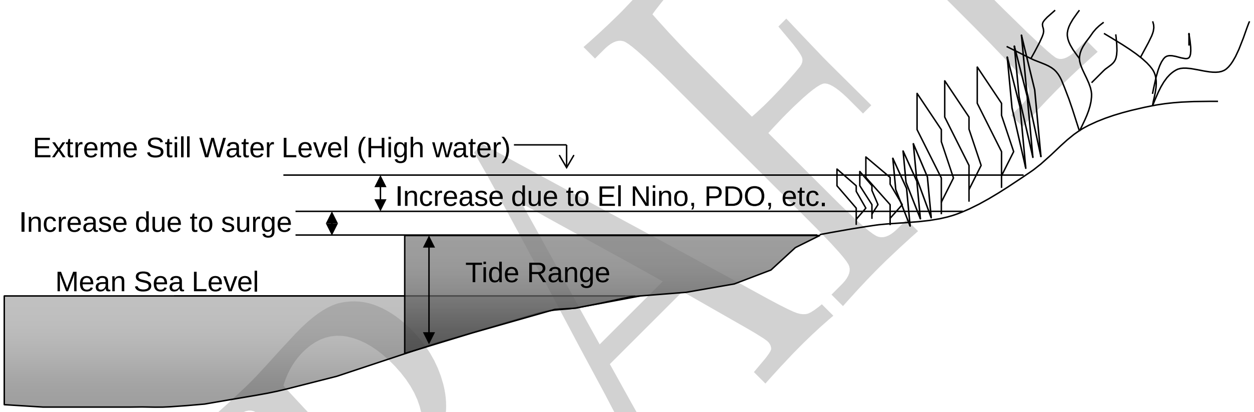


Figure 12. Changes to Extreme Still Water Level due to Surge, El Niños, PDOs, and such (Figure by L. Ewing, 2013).

Table 12. General Resources for Determining Still Water Elevation due to Surge, El Niños, PDOs.

Resource	Specifics of Information	Source
Sea-Level Rise Affecting Marshes Model (SLAMM)	Simulates the dominant processes involved in wetland conversions and shoreline modifications during long-term sea-level rise. Map distributions of wetlands are predicted under conditions of accelerated sea-level rise, and results are summarized in tabular and graphical form.	http://www.warrenpinnacle.com/prof/SLAMM
NOAA Digital Coast Sea-Level Rise Viewer	Displays potential future sea levels within wetland areas, and provided visualizations for various amounts of sea-level rise. For bays and estuaries, it also provides information on inland areas with the potential to flood if existing barriers to water connectivity are removed or overtopped. Communicates spatial uncertainty of mapped sea-level rise, overlays social and economic data onto sea-level rise maps, and models potential marsh migration due to sea-level rise. Maps do not include any influence of beach or dune erosion.	http://www.csc.noaa.gov/digitalcoast/tools/slrviewer
Pacific Institute Sea-Level Rise Maps	Downloadable PDF maps showing the coastal flood and erosion hazard zones from the 2009 study. Data are overlayed on aerial photographs and show major roads. Also available are an interactive online map and downloadable maps showing sea-level rise and population and property at risk, miles of vulnerable roads and railroads, vulnerable power plants and wastewater treatment plants, and wetland migration potential.	http://www.pacinst.org/reports/sea_level_rise/maps/ For the 2009 report "The Impacts of Sea-Level Rise on the California Coast" visit: http://www.pacinst.org/reports/sea_level_rise/report.pdf
Cal-Adapt – Exploring California's Climate	Shows coastal areas that may be threatened by flooding from a 1.4 meter rise in sea level and a 100-year flood event. Maps do not now include any influence of beach or dune erosion or existing protective structures.	http://cal-adapt.org/sealevel/

***Outcomes from Step 5**: Step 5 provides estimates of water elevations that can result from surge, El Niños and PDOs. When combined with the sea level changes to the tidal range, developed in Step 4, this can provide information on the extreme still water level. For most open coast situations, this information will be used to inform further project analysis and planning that examines erosion, surge and storm conditions.*

Step 6 – Estimate Beach, Bluff and Dune Change from Erosion

Predictions of future beach, bluff, and dune erosion are complicated by the uncertainty associated with future waves, storms and sediment supply. As a result, there is no accepted method for predicting future beach erosion. At a minimum, projects should assume that there will be inundation of dry beach and that the beach will continue to experience seasonal and inter-annual changes comparable to historic amounts. When there is a range of erosion rates from historic trends, the high rate should be used to project future erosion with rising sea level conditions. For beaches that have had a relatively stable long-term width, it would be prudent to also consider the potential for greater variability or even erosion as a future condition. For recent studies that provide some general guidance for including sea-level rise in an evaluation of bluff and dune erosion, see, for example, Heberger et al. (2009) or Revell (2011). Other approaches that recognize the influence of water levels in beach, bluff, or dune erosion can also be used. Table 13, at the end of this section, provides some resources that can be used for projecting future erosion.

The following sections discuss specific concerns associated with beach, bluff and dune erosion and are provided to acquaint readers to the main issues associated with each system. Readers with a strong background in coastal systems may want to skim or skip the rest of this section.

Beach Erosion

Beach erosion and accretion occur on an on-going basis due to regular variability in waves, currents and sand supply. The movement of sand on and off of beaches is an ongoing process. Along the California coast, periods of gradual, on-going beach change will be punctuated by rapid and dramatic changes, often during times of large waves, or high streamflow events.

The overall dynamics of beach change have been described many times[40]. Sand moves both on and off shore as well as along the shore. Normal sources of sand to a beach are from rivers and streams, bluff erosion or gullies, and from offshore sand sources. Sand leaves a beach by being carried downcoast by waves and currents, either into submarine canyons or to locations too far offshore for waves to move it back onto shore. Beaches are part of the larger-scale sediment dynamics of the littoral cell, and in very simple terms beaches accrete if more sand comes onto the beach than leaves and beaches erode if more sand leaves than is added. Changes in sand supply are a major aspect of beach change.

[40] See for example, Bascom, 1980; Komar, 1998; Griggs et al., 2005.

Beach changes are often classified as being either seasonal or long-term/inter-annual changes. Seasonal changes are the shifts in beach width that tend to occur throughout the year and are usually reversible. Beaches tend to widen during the late spring and summer as gentle waves carry offshore sand up, onto the beach. Then during late fall and winter, beaches tend to become narrower as more high energy waves carry sand away from the beach and deposit in offshore bars. This is followed by beach widening as gentler waves again bring sand landward, building up a wider dry-sand summer beach. These changes are considered seasonal changes, and if the beach widths return to the same seasonal width each year, then the beach experiences seasonal changes but no long-term or inter-annual changes. If the seasonal beach widths become progressively narrower, these changes become long-term or inter-annual change and suggest a long-term beach change trend – accretion if the beach is widening and erosion if the beach is narrowing.

If development is at or near beach level, erosion of the beach can expose the development to damage from wave forces, flooding, and foundation scour. And waves that hit the coast bring with them vegetation, floating debris, sand, cobbles, and other material. This material can act like projectiles, adding to the flood damage and forces from the waves.

At present, about 66% of the California beaches have experienced erosion over the last few decades, with the main concentration of eroding beaches occurring in southern California (Hapke et al., 2006). This erosion has been due to a combination of diminished sand supplies and increased removal of sand by waves and currents. With rising sea level, beach erosion is likely to increase, due to both increased wave energy[41] that can carry sand offshore or away from the beach, and to decreased supply of new sediments to the coast[42].

There are several elements that will contribute to the effects of sea-level rise on seasonal and inter-annual beach change. There will be the changes to the beach due to inundation by rising water levels, as shown in Figure 13. (See discussion on inundation for more information on how to determine this change.) If the beach cannot migrate inland to accommodate these changes, then the inundation will result in a direct loss or erosion of beach width. This will result in a narrower seasonal beach as well as inter-annual loss of beach.

Seasonal and inter-annual beach conditions will also be affected by changes to waves and sediment supply. Since waves are sensitive to bottom bathymetry, changes in sea level may change the diffraction and refraction of waves as they approach the coast, and change the resulting mixture of beach-accreting and beach-eroding waves. However, the influence of climate change (not just rising sea level) on wave conditions, through changes in wave height, wave direction, storm frequency and storm intensity will likely be far more significant than the slight changes from bathymetric changes. In addition, changing precipitation patterns will modify the amount and timing of sediment delivery to the beach.

[41] In shallow water, wave energy is proportional to the square of the water depth. As water depths increase with sea-level rise, wave energy at the same location will likewise increase.
[42] Many parts of the developed coast are already experiencing drops in sand supplies due to upstream impoundments of water and sediment, more impervious surfaces, and sand mining.

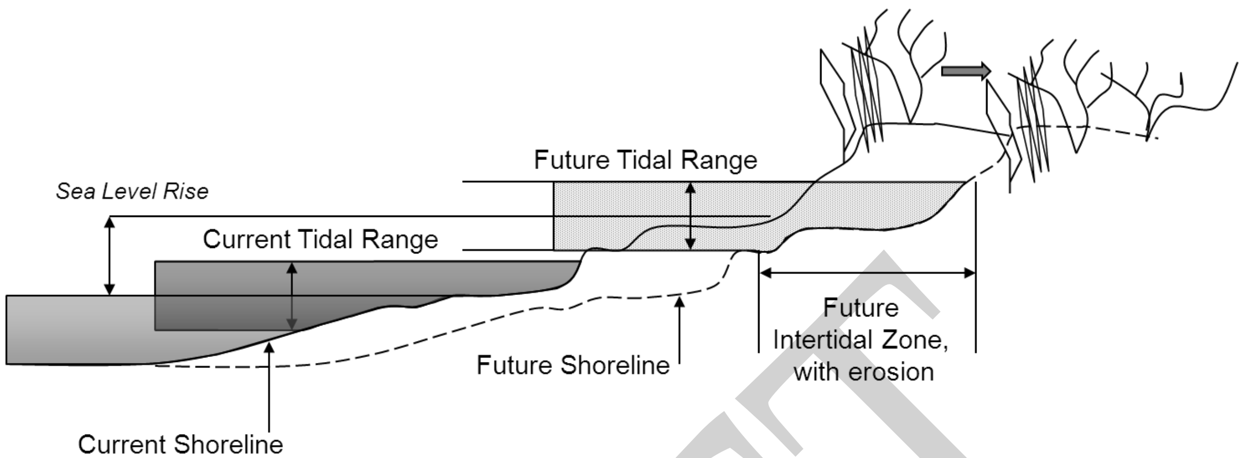


Figure 13. Changes to the Intertidal Zone with Sea-level rise and Erosion, without Wave Impacts (Figure by L. Ewing, 2013).

<u>Bluff Erosion</u>
A second type of erosion occurs on coastal bluffs[43]. There is no fully-accepted methodology for estimating future bluff erosion with sea-level rise. Guidance for coastal analysts in Hawaii is to assume erosion will increase as a proportion of historic erosion. (Hwang, 2005) One approach used in the past by the Commission has been to use the high range of historic erosion rates to represent average future trends. A more process-based methodology, used in the Pacific Institute study of erosion due to rising sea level, is to correlate future erosion rates of bluffs with increased frequency of wave impacts (Heberger et al., 2009; Revell, 2011). This approach assumes that all bluff erosion is due to wave impacts and erosion rates will change over time as the beach or bluff experiences more frequent or more intense wave attack. Such an approach should be considered for examining bluff erosion with rising sea level. Other approaches that recognize the influence of water levels in beach, bluff, or dune erosion can also be used.

Bluff retreat occurs due to many different mechanisms. Landslides, slumps, block failures, gullies, and rilling are examples of bluff retreat. At the most basic level, bluff retreat or collapse occurs when the forces leading to collapse of the bluff face are stronger than the forces holding the bluff in place. Forces causing bluff retreat can include earthquakes, wind, burrowing animals, gravity, rain, surface runoff, groundwater, and sheet flow. Coastal bluffs have the added factor of wave attack, a factor that is not present for inland bluffs. Resistance to collapse is mainly a characteristic of the bluff material. For example, granitic bluffs like those along the Big Sur coast retreat at a much slower rate than the soft sandstone and marine terrace bluffs of Pacifica.

[43] Bluffs can be built or expanded during interglacial cycles or following seismic uplift. Many of the marine terraces that are visible along the California coast are remnants of past beach areas that have been uplifted to become bluffs and cliffs. However, natural bluff rebuilding is a millennial or multi-millennial process, and it will not occur during the time periods over which most development projects are evaluated.

Coastal bluff erosion can occur throughout the year, but it often occurs during or after storm periods, when the dry beach will be narrow or non-existent. When coastal bluffs are fronted by wide sand beaches, most waves break on the beach face and the beaches protect the bluffs from direct wave attack. When the beach is narrow, there is less buffering of the wave energy and waves can break directly against the bluffs. A general depiction of bluff retreat with rising sea level is provided in Figure 14.

Bluff retreat is often episodic – the bluff may be stable for a number of years and then retreat by tens of feet in a few hours or a few days. If the changes to a bluff are examined through endpoint analysis – i.e. looking first at the initial position of the bluff and then at the position of the bluff sometime in the future, researchers can determine the amount of retreat that has occurred during the time from the initial to final positions. This gives information on an average retreat rate that has occurred, but gives no information about the conditions leading to the retreat, or the progression of retreat and no retreat. The average retreat rates can give some indication of likely future changes, but they provide little information about when the next retreat episode might occur or how large it might be.

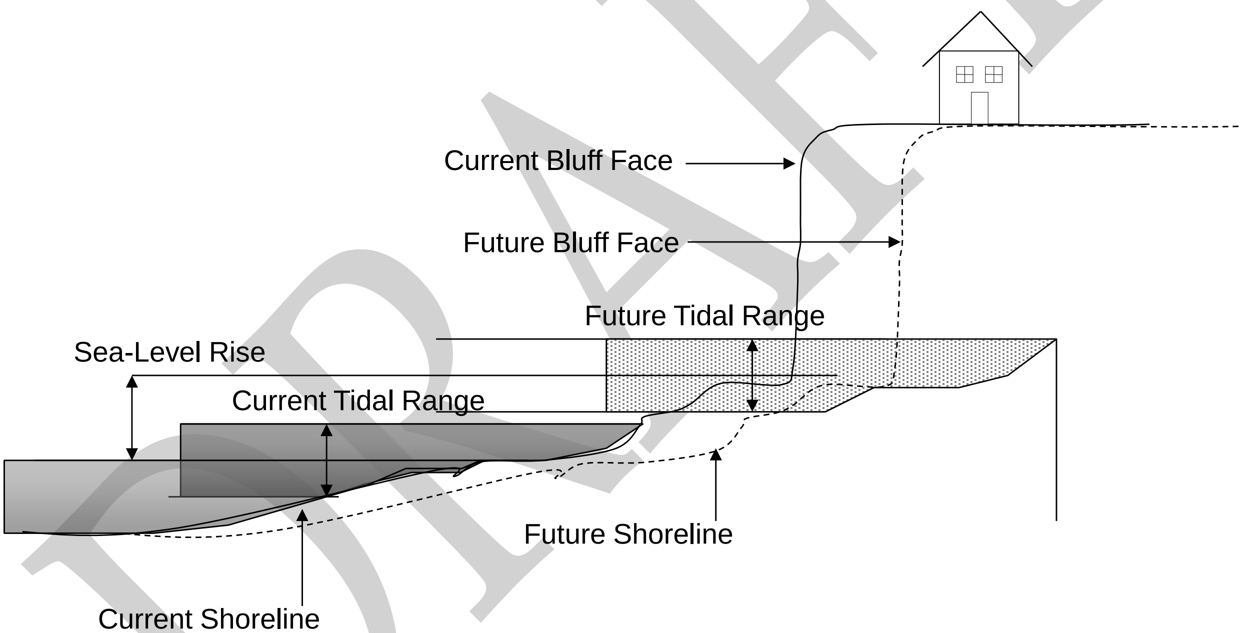


Figure 14. Bluff Erosion with changes in sea level (Figure by L. Ewing, 2013).

Dune Erosion

Just as there is no fully accepted methodology for estimating changes to beach or bluff erosion with sea-level rise, there is no fully-accepted methodology for dune erosion. A methodology somewhat similar to that for bluff erosion has been developed for dunes (Heberger et al., 2009; Revell, 2011), and such an approach should be considered for examining dune erosion with rising sea-level. Other approaches that recognize the influence of water levels in beach, bluff or dune erosion can also be used.

Dune erosion occurs when the waves break at or near the dunes, pulling sediment out of the dune. This process does deposit sand onto the beach or in the nearshore area, but can result in short term dune retreat. If sand is not returned to the dunes following these periods of short-term retreat, the sand losses will contribute to long-term dune erosion. When development is on the coastal dune, building damage occurs when the dune retreats back to the location of development, either through reversible, short-term retreat or long-term erosion. As with bluff erosion, the Pacific Institute work (Heberger et al., 2009) examined sea level related changes in dune erosion rates and has provided a methodology that can be considered in examining future changes to dune erosion with increased sea-level rise.

For individual cases, determinations of future retreat risk are based on the site-specific conditions, and professional analysis and judgment. However, the lack of information about the contributions of all the erosive forces to dunes and the beach-dune interactions makes it challenging to anticipate future changes to coastal dune retreat due to rising sea level and increased wave forces. As with beaches and bluffs for most situations, these historic conditions provide a lower limit for future dune retreat, or the upper limit of advance for those sites that are now experiencing accretion or quasi-stability. Projections of future erosion should either (1) use the high range of historic erosion, (2) develop a sea-level rise influenced erosion rate, as done by Heberger et al., 2009 or Revell, 2011, or (3) develop another approach that considers shoreline changes that are likely to occur under rising sea level conditions.

Table 13. General resources for information on beach, bluff and dune erosion

Resource	Specifics of Information	Source
Aerial Photographs	Useful for general information on shoreline trends Ortho-rectified photos can help quantify trends	California Coastal Records Project - www.californiacoastline.org; Huntington Library; Local Libraries
LIDAR	Fairly detailed topography Can provide GIS layers for current conditions Comparable with LIDAR data sets for temporal changes	NOAA Coastal Services Center - http://www.csc.noaa.gov/data/index.html
USGS National Assessment of Shoreline Change with GIS Compilation of Vector Shorelines	Statewide inter-annual beach and bluff erosion. GIS shorelines available for sandy shorelines & cliff edge. Shorelines show historic changes. Long-term (70 to 100 years); short-term (25 to 50 years. No projections of future erosion rates.	Sandy Shorelines -- Open File Report 2006-1219; GIS Data in Open File 2006-1251 http://pubs.usgs.gov/of/2006/1219 and http://pubs.usgs.gov/of/2006/1251 Bluff Shorelines – Open File Report 2007-1133; GIS Data in Open File 2007-1251 http://pubs.usgs.gov/of/2007/1133 and http://pubs.usgs.gov/of/2007/1112
Regional Sediment Management Studies	Summaries of seasonal and long-term erosion studies	CSMW Website; http://dbw.ca.gov/csmw/default.aspx

Corps of Engineers, Coast of California Studies	Summaries of seasonal and long-term erosion studies	Studies for many regions are available through an internet search. Addresses are too numerous to list here.
Beach Profiles and Surveys	Detailed Beach or Bluff changes with time	NOAA, Coastal Services Center - http://www.csc.noaa.gov/data/index.html; US Army Corps of Engineers; Regional Beach Studies; University Studies
The Impacts of Sea-level rise on the California Coast (Pacific Institute Report)	Show expected changes to bluff position over time for sea-level rise of 1.4 meters from 2000 to 2100 for California coast from Oregon border through Santa Barbara County.	Pacific Institute Web site - http://www.pacinst.org/reports/sea_level_rise/maps/
CoSMoS	COSMOS is a tool for predicting climate change impacts from storms. It does not predict long-term erosion, but can provide general information for short-term, storm-drive beach changes. Only available, at present, for the central coast.	http://data.prbo.org/apps/ocof/

Outcome from Step 6: *Step 6 provides projections of future long-term beach, bluff or dune erosion that takes into account sea-level rise. For locations without any influence from storm surge, or wave energy, the identification of the extent of beach, bluff or dune erosion may be sufficient for project analysis and planning efforts. This projected new erosion area may also be useful for anticipating the appropriate setback distance for otherwise stable land forms (If slope stability if a concern, refer to Commission guidance on setbacks (Johnsson 2005. Available: http://www.coastal.ca.gov/W-11.5-2mm3.pdf)). For most open coast situations, this information will be used to inform further project analysis and planning that examines erosion, surge and storm conditions.*

Step 7 – Determine Wave, Storm Wave, Wave Runup and Flooding Conditions

The main concerns with waves, storm waves, and runup are flooding and wave impacts. Flooding is the temporary wetting of an area by waves, wave runup, surge, atmospheric forcing (such as water elevation during El Niño events) and, at river mouths, the combination of waves and river flows. Wave impacts occur when high-energy waves, often associated with storms, reach backshore areas or development. Coastal flooding and wave impacts are worst when they coincide with high water level events (high tide plus high inundation). As sea level rises, inundation will move inland, and so will flooding and wave impacts. Beach erosion will aggravate these conditions and add to the inland extent of impacts.

Flooding: In most situations, factors that result in high water conditions, such as tides, surge, El Niños, and PDOs, should be used to determine flood conditions and flood areas, as shown below. If the area is exposed to storm waves, these forces should be examined as well.

Future Flooding = Future Higher High Tide + Surge + Forcing + Wave Runup

Flooding Areas = Flooding + seasonal eroded beach + long-term beach erosion

Waves: Wave impacts depend greatly upon storm activity – both the intensity and the duration of the storm. Normally projects have used design wave conditions comparable to the 100-year event. For critical infrastructure or development with a long anticipated life expectancy it may be advisable to use a greater design standard, such as a 200-year or 500-year event. So, some proposed projects may want to adjust design waves or frequency of high energy waves to analyze the consequences of worsening wave impacts.

Wave impacts to the coast, to coastal bluff erosion, and to inland development should be analyzed under the conditions most likely to cause harm. Those conditions normally occur in winter when most of the sand has moved offshore, leaving only a reduced dry sand beach to dissipate wave energy. Since the development will be in place for a number of years, on beaches that will experience long-term erosion, the beach changes expected to occur over the life of the development should also be considered. Just as the beach conditions should be those least likely to protect from damage over the life of the development, so too should the water level conditions be those most likely to contribute to damage over the life of the development. Waves that cause significant damage during high tide will be less damaging during low tide; all other things being equal, waves will cause more inland flooding and impact damage when water levels are higher. Since water levels will increase over the life of the development due to rising sea level, the development should be examined for the amount of sea-level rise (or a scenario of sea-level rise conditions) that is likely to occur throughout the expected life of the development. Then, the wave impact analysis will examine the consequences of a 100-year design storm event, with water levels likely to occur due to high water conditions and sea-level rise, and with a long-term and seasonally eroded beach.

Eroded Beach Conditions = seasonal erosion + long-term erosion*

High Water Conditions = High tide + relative sea-level rise* + atmospheric forcing

Wave Conditions = 100-year Design Storm + High Water + Eroded Beach

* The time period for both long-term erosion and relative sea-level rise will be at least as long as the expected life of the development.

The remaining discussion provides general information about waves, the California wave climate and coastal flooding. It is provided to acquaint readers to the main issues associated with waves and coastal flooding. Readers with a strong background in waves or coastal processes may want to skim or skip the rest of this section.

Waves, like tides, cause constant changes to the water levels that are observed at the coast. The rhythmic lapping of waves on the beach during summer can be one of the joys of a beach visit. At other times of the year, waves can increase in size and energy and damage or destroy buildings, and cause erosion of bluffs and cliffs. Routine ocean waves are generated by wind blowing across the surface of the water. Once generated, waves can travel far from their source, combining with waves generated from other locations, resulting in the rather erratic and choppy water levels that are seen in most of the ocean. But, as waves move into shallow water and approach land, they take on a more uniform appearance, aligning somewhat parallel to the shoreline through processes of refraction and diffraction. During most of the year, moderate short-period waves break once they are in water depths of approximately 1.3 times the wave height.

Storm Waves: During storm conditions, winds can transfer large amounts of energy into waves, increasing the wave height, length and period. Energy transfer to waves depends upon three conditions, the wind energy that is available to be transferred to the water (intensity), the length of time over which the wind blows (duration), and the area over which the wind blows (the fetch). As any of these conditions increase, the energy in the waves will increase, as will the energy that these waves bring to the coastline. Coastal scientists separate waves that are generated far from the coast (swell) from waves that are locally generated (seas). Storms in the mid-Pacific can cause storm-like wave conditions along the coast, even when there are no storms in the area. Likewise, a local storm can cause storm waves along one part of the coast while waves in other sections of the coast may be fairly mild.

Some of the worst storm wave conditions occur when there are intense storms along a large portion of the coast, and when this large, distantly generated swell combines with local seas. This was the case during part of the 1982-83 El Niño storm season when waves from a distant storm combined with locally generated waves and made landfall during high tide. As a result, approximately 3,000 homes and 900 businesses were damaged, and 33 buildings were destroyed. Damages exceeded $100 million to structures and $35 million to public recreational infrastructure (in 1982 dollars) (Flick, 1998).

Wave Runup: Wave runup, as depicted in Figure 15, is the distance or extent that water from a breaking wall will extend up a beach or structure. Much of the wave energy will dissipate during breaking, but wave runup can also be damaging. The runup water moves quickly; it can scour or erode the beach, damage structures, and flood inland areas.

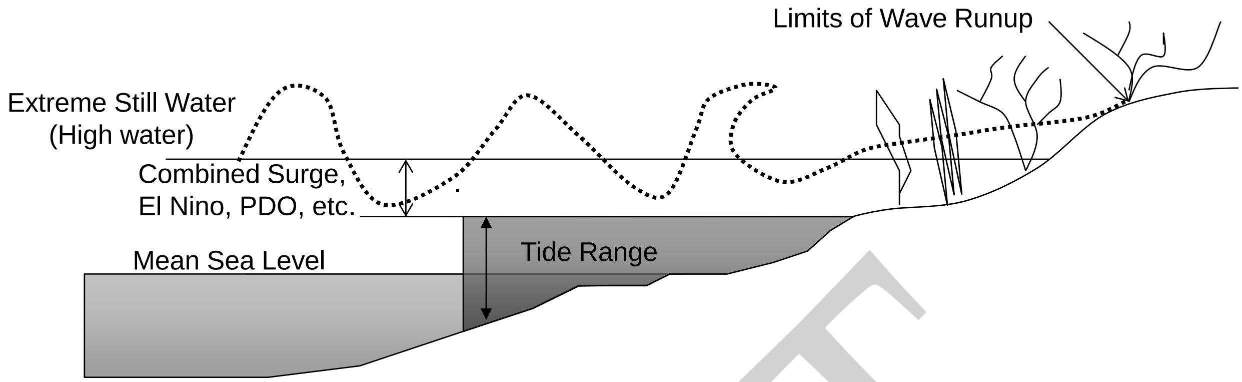


Figure 15. Wave Runup combined with Extreme Still Water (High Water) (Figure by L. Ewing, 2013).

Damage from waves and wave runup may increase in the future, due both to rising sea level and to changes in storm intensity and frequency. Waves will break farther landward when water levels are higher. Therefore, increased water levels due to tides, surge, ENSO or PDO variability, or sea-level rise will enable more wave energy to reach the beach, back shore, or inland development. The higher water levels do not change the waves. Rather, higher water levels change the point of impact, the extent of runup, and the frequency of wave impact. In locations where high waves now hit the coast, that frequency will increase. In locations where high waves rarely hit the coast, exposure to wave impacts will increase. Increased exposure to wave impacts or wave runup can cause a greater risk of flooding, erosion, and/or bluff failure.

Summary: Coastal flooding is a significant problem now and it will increase with rising sea level. At present, about 210,000 people in California are living in areas at risk from a 100-year flood event (Heberger et al., 2009). A rise in sea level of 55 inches (1.4 meters) and with no change in development patterns or growth along the coast, could put 418,000 to 480,000 people at risk from a 100-year flood (Cooley et al., 2012). Increases in storm intensity, or in the density of development in flood-prone areas, will increase the number of people at risk from flooding.

The frequency and intensity of high wave events depends upon the storm conditions that generate the waves. There is less consistency in the output of climate models related to projections of future storm conditions than there has been for temperature projections. A recent report on coastal flooding from 2000 to 2100 for the California coast has found that "storm activity is not projected to intensify or appreciably change the characteristics of winter nearshore wave activity of the twenty-first century." (Bromirski et al., 2012, p. 33) This continuation of current storm conditions is not, however, an indication that storms will not be a problem in the future. Storm damage is expected to continue, and, if sea-level rise by the end of the twenty-first century is close to the high projections of about 55 inches (1.4 meters), "coastal managers can anticipate that coastal flooding events of much greater magnitude than those during the 1982-83 El Niño will occur annually." (Bromirski et al., 2012, p. 36)

For most situations, the 100-year storm event will be used as the design storm. This is equivalent to a storm with a 1% annual probability of occurrence. However, most development does not stay for only a year and this probability of occurrence grows over time such that there is a 25% probability of occurrence during 25 year and over 55% probability that this storm will occur at least once during a 75 year period. Even so, the 100-year storm event, like the 100-year flood event, is often used as a design standard for development. However, for structures with a very long projected life or for which storm protection is very critical, a larger, 200-year or 500-year event might be appropriate.

Table 14 lists many of the resources that are available for finding regional or state-wide information on waves and flooding. Local communities often may have records of major erosion episodes or flood events.

Table 14. General Resources for Flooding and Wave Impacts

Resource	Specifics of Information	Source
CDIP (Coastal Data Information Program)	Current and historic information on wind, waves, and water temperature, wave and swell models and forecasting. As of 2013, there are 19 active stations along the California coast.	http://cdip.ucsd.edu/
Flood Insurance Rate Maps (FIRMs)	FEMA is updating coastal flood maps. Existing FIRMs are based on 1980s topography; flooding includes seasonal beach change but not long-term erosion. Maps do not include sea-level rise. Inclusion of a site shows a flood hazard; but exclusion does not necessarily show a lack of flood hazard.	FEMA Flood Map Center
Regional Sediment Management Studies	Some studies show elements of beach flooding and wave impacts	CSMW Website - http://dbw.ca.gov/csmw/default.aspx
Cal-Adapt – Exploring California's Climate	Shows coastal areas that may be threatened by flooding from a 1.4 meter rise in sea level and a 100-year flood event. Maps do not now include any influence of beach or dune erosion or existing protective structures.	http://cal-adapt.org/sealevel/
FEMA Flood Hazard Mapping Guidance	Subsection D.2.8 provides guidance for calculating wave runup and overtopping on barriers. There are special cases for steep slopes and where runup exceeds the barrier or bluff crest.	http://www.fema.gov/library/file?type=publishedFile&file=frm_cfhamagd28.pdf&fileid=73be5370-c373-11db-a8db-000bdba87d5b
US Army Corps of Engineers, Coastal Engineering Manual	Detailed information on all aspects of deepwater wave transformation, shoaling, runup, and overtopping.	http://chl.erdc.usace.army.mil/cem

European Overtopping Manual	Descriptions of available methods for assessing overtopping and its consequences. Provides techniques to predict wave overtopping at seawalls, flood embankments, breakwaters and other shoreline structures facing waves. Supported by web-based programs for the calculation of overtopping discharge and design details	http://www.overtopping-manual.com/
CoSMoS	COSMOS is a tool for predicting climate change impacts from storms. It does not predict long-term erosion, but can provide general information for short-term, storm-drive beach changes. Only available, at present, for the central coast.	http://data.prbo.org/apps/ocof/
OCOF	(See CoSMoS)	http://data.prbo.org/apps/ocof/

Outcome from Step 7: *Step 7 provides projections of future flooding and wave impacts resulting from waves, storm waves and runup, that takes into account sea-level rise.*

Step 8 – Examine potential flooding from extreme events

Extreme events[44], by their very nature, are beyond the normal events that are considered in most shoreline studies. For an individual storm, that might be one with an intensity at or above the 100-year event. Or, extreme events could arise from a series of large, long-duration storms during high tides or from a local storm that coincides with the arrival of distant swell and high tides. Global sea-level rise greater than that projected to occur by 2100, when combined with a large storm during normal tides could develop into an extreme event. Rapid subsidence, as might happen along the northern CA coast during a Cascadia Subduction Zone earthquake, would be an extreme event. These are the outlier events that need to be anticipated and their consequences will need to be considered in planning and project analysis. In many situations, this consideration might be qualitative with consideration for the consequences that could happen if an extreme event does occur and opens up opportunities to address some of those consequences through design and adaptation.

In California, there may be some worsening of extreme precipitation and inland flooding from projected changes to atmospheric rivers. In general, however, future extremes are likely to be comparable to the extremes of today, but with the added influence of sea-level rise. Extreme

[44] In its report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, the IPCC defines extreme events as “a facet of climate variability under stable or changing climate conditions. They are defined as the occurrence of a value or weather or climate variable above (or below) a threshold value near the upper (or lower) ends (“tails”) of the range of observed values of the variable” (IPCC, 2012).

storm waves or floods can be addressed with the guidance provided earlier, except that the extreme storm conditions would be used. For tsunamis it is recommended that, for most situations, the appropriate projection of sea-level rise be added to the currently projected inundation level from tsunamis. This will provide a close approximation for future inundation from extreme tsunamis. If detailed analysis of future tsunami impacts is needed, someone experienced in modeling tsunami waves should be contacted.

Tsunamis: Tsunamis are large, long-period waves that can be generated by submarine landslides, large submarine earthquakes, meteors, or volcanic eruptions. They are rare events, but can be extremely destructive when they occur. There has been no research that suggests tsunamis could worsen in the future through some link with climate change. However the extent of tsunami damage will increase as rising water levels allow tsunami waves to extend farther inland. Thus the tsunami inundation zone will expand inland with rising sea level. There is no direct connection between tsunamis and either sea-level rise or climate change. But, for coastal areas that are at risk from tsunamis, the inundation zone will change as sea-level rises.

The detailed changes to the inundation zone with rising sea level would need to be determined by modeling. However, modeling of long-waves, such as tsunamis, is a specialized area of coastal engineering, and will not be covered in this general guidance. For most situations, it will be sufficient to get information on possible inundation from the most recent tsunami inundation maps (currently on the Department of Conservation website, http://www.conservation.ca.gov/cgs/geologic_hazards/Tsunami/Inundation_Maps/Pages/Statewide_Maps.aspx). As a rough approximation, the change to the inundation level can be estimated as equal to the change water elevation due to sea level. So, a one-foot rise in sea level could be assumed to result in a one-foot rise in the inundation elevation. However, in many places, particularly shallow bays, harbors, and estuaries, the change in tsunami inundation zone is likely to scale non-linearly with sea-level rise and require careful modeling. In areas with high tsunami hazards, or where critical resources are at risk, a site-specific analysis of sea-level rise impacts on tsunami hazards is crucial and someone experienced in modeling tsunami waves should be contacted.

Summary: Many different factors affect the actual water levels that occur along the coast and resulting hazards. In California, waves and tides have the largest routine effect on water levels. Tsunamis may have a very large, but infrequent effect of water levels. Sea-level rise will affect water levels all along the coast. Until the mid-century, the effects of tides and storms are expected to have the biggest effect on local water levels, with sea-level rise being a growing concern. For the second half of the century, sea-level rise is expected to become increasingly important for water levels and in damages to inland areas from flooding, erosion and wave impacts. Table 15 provides a general characterization of all the factors that can affect local water levels, with general estimate of their range and frequency of occurrence.

Table 15. Factors that Influence Local Water Level Conditions

Factors Affecting Water Level	**Typical Range for CA Coast (m)**	**Typical Range for CA Coast (feet)**	**Period of Influence**	**Frequency**
Tides	1 – 3	3 – 10	Hours	Twice daily
Low pressure	0.5	1.5	Days	Many times a year
Storm Surge	0.6 – 1.0	2 – 3	Days	Several times a year
Storm Waves	1 - 5	3 – 15	Hours	Several times a year
El Niños (within the ENSO cycle)	< 0.5	<1.5	Months - Years	2-7 years
Tsunami waves	6 – 8	20 – 26	Minutes to Hours	Infrequent but unpredictable
Historic Sea Level, over 100 years	0.2	0.7	On-going	Persistent
NRC State-wide Sea Level Projections 2000 – 2050	0.2 – 0.4	0.7 – 1.4	Ongoing	Persistent
NRC State-wide Sea Level Projections 2000 - 2100	0.1 – 1.43 m (North of Cape Mendocino) 0.42- 1.67 m (South of Cape Mendocino	0.3 – 4.69 ft (North of Cape Mendocino) 1.38 – 5.48 ft (South of Cape Mendocino)	Ongoing	Persistent

NOTE: All values are approximations. The conversions between feet and meters have been rounded to maintain the general ranges and they are not exact conversions.
Sources: Flick, 1998; NRC, 2012; Personal communications from Dr. Robert Guza (Scripps Institution of Oceanography) and Dr. William O'Reilly (Scripps Institution of Oceanography and University of California, Berkeley); and personal judgment of staff.

Outcome from Step 8: *Step 8 provides projections of potential flooding from extreme events including rapid subsidence, extreme precipitation, and tsunamis.*